

# A Cepheid distance to NGC 4258

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Distances measured using Cepheid variable stars have been essential for establishing the cosmological distance scale and the value of the Hubble constant. These stars have remained the primary extragalactic distance indicator since 1929 because of the small observed scatter in the relationship between their pulsation period and luminosity, their large numbers, which allow many independent measures of the distance to a galaxy, and the simplicity of the basic physics underlying their variability. Poten-

tial systematic uncertainties in the use of the Cepheid period-luminosity relation to determine distances are estimated to be  $8 - 10\%$ <sup>[1]</sup>. Here we describe the results of a search for Cepheids in the nearby galaxy NGC 4258, which has an independently determined geometric distance of  $7.2 \pm 0.5$  Mpc<sup>[2]</sup>. We determine a Cepheid distance of  $8.1 \pm 0.4$  (excluding possible systematic errors affecting Cepheid distances) Mpc; there is a  $1.3\sigma$  difference between the measurements. If the maser-based distance is adopted and other Cepheid distances are revised according to our results, the derived value of the Hubble constant would be increased by  $12 \pm 9\%$ , and the corresponding age of the Universe would decrease by the same factor.

Over the last 20 years, substantial improvements have been made in the Cepheid distance scale<sup>[3, 4, 5]</sup>. The Cepheid period-luminosity (P-L) relation derived from observations of stars in the Large Magellanic Cloud (LMC) has formed the basis for the calibration of the HST Key Project on the Extragalactic Distance Scale (<sup>[6]</sup> henceforward, the Key Project) and of many other recent extragalactic distance measurements<sup>[7]</sup>. Cepheid distances to galaxies as far away as 25 Mpc have been reliably measured using the Hubble Space Telescope (HST) with random errors of a few percent; the results have been used to calibrate a number of secondary distance methods and thereby to provide estimates of the Hubble constant.

Today, the largest identified potential sources of systematic error in the Cepheid distance scale are the zero point of the Cepheid period-luminosity relation (or alternatively, the adopted distance to the LMC), difficulties in the calibration of the HST Wide Field and Planetary Camera 2 (WFPC2) camera which has been used for most modern studies, and the possible effects of differences in the chemical composition of stars on Cepheid distance measurements. These have been judged to be  $\pm 6.5\%$ ,  $\pm 4.5\%$ , and  $\pm 4\%$  in distance, respectively<sup>[1]</sup>, with substantial non-Gaussianity possible; for instance, recently published measurements of the distance to the LMC range from about 40 to about 55 kpc, with a distribution skewed towards lower values<sup>[8]</sup>. Given the

remaining uncertainties affecting the application of the LMC-calibrated Cepheid period-luminosity relation to galaxies observed with HST, further tests of the extragalactic distance scale are clearly important.

The spiral galaxy NGC 4258 presents new opportunities to test and potentially to improve the calibration of the Cepheid P–L relation because of the precision with which its distance has been measured in a manner independent of the conventional ladder of astronomical distance scales<sup>[9]</sup>. This distance, 7.2 Mpc, has been determined using its apparently simple, Keplerian circumnuclear disk delineated by line-emitting water masers that orbit a supermassive black hole at its center<sup>[10],[11]</sup>. The total estimated uncertainty in this distance is  $\pm 0.3$  Mpc if the disk is presumed to be circular; if nonzero eccentricities are allowed, the uncertainty increases to  $\pm 0.5$  Mpc (we adopt this value for all further discussion). The direct, geometric methods used are believed to have minimal unknown systematic uncertainties. Combining the observed rotation velocities with the measured centripetal acceleration in the disk<sup>[12]</sup> or the observed proper motions of the maser sources<sup>[2]</sup> allows independent measurements of the physical size of the disk; comparing these to its observed angular extent yields the distance to the galaxy center via simple geometry. The two routes to this distance (proper motions and accelerations) yield results in agreement with each other to 1%.

We have therefore observed a portion of NGC 4258 to search for Cepheids using the WFPC2 camera and the Hubble Space Telescope on 11 epochs in 1998 with both the *F555W* and *F814W* filters. Details of the observations and the analysis procedures summarized here will be described elsewhere (Newman *et al.* 2000, in preparation); full photometric results and other additional figures and tables are also given there. We have performed point-spread-function fitting photometry on these data with two commonly-used software packages – DAOPHOT/ALLFRAME<sup>[13]</sup> and DoPHOT<sup>[7, 14]</sup> – following Key Project-like procedures throughout<sup>[17]</sup>, and converted results to standard *V* and *I* filter photometric systems. Cepheid searches were performed using two different algorithms with the ALLFRAME dataset<sup>[15, 16]</sup>, and using a third for DoPHOT data<sup>[17]</sup>.

We have identified and determined light curves, periods, mean magnitudes, and colours for 15

Cepheids. All of these stars fulfill four criteria: they are identified as variable by all three search techniques, fit a Cepheid template light curve with reasonable  $\chi^2$ , visibly vary in blink comparisons in both  $F555W$  and  $F814W$  images, and have negligible statistical probability of being misidentified nonvariables. Light curves illustrating the variability of several of the Cepheids found are plotted in Figure 1. The DoPHOT NGC 4258 P–L relations are plotted in Figure 2. We have adopted the DoPHOT photometry for all major conclusions reported here, as ALLFRAME photometry yielded internally discrepant distances from Cepheids on the two WFPC2 chips used (by 0.24 mag, a  $1.8\sigma$  difference possibly due to an error in aperture corrections), whereas the corresponding DoPHOT results agreed to within 0.07 mag ( $0.5\sigma$ ); however, as an additional check we also provide ALLFRAME values in much of what follows.

In Key Project procedures, the differences between the observed and intrinsic colours of Cepheids are then used to correct for the effects of extinction by dust assuming a standard Galactic reddening law<sup>[18]</sup>. Applying this correction star-by-star and then robustly averaging yields results for small datasets that best match those that would be obtained using Key Project methods with more Cepheids (Newman *et al.* 2000, in preparation), so we adopt this as our primary method of determining a distance modulus for NGC 4258. This technique yields a distance with a statistical uncertainty (derived from the P–L relation fit) of  $\pm 0.07$  mag. Based upon past experience with Key Project galaxies, we would expect a possible  $1\sigma$  systematic error of  $\pm 0.04$  mag from the uncertainties in photometry due to the difficulty of obtaining accurate aperture corrections in our fields, which contained relatively few bright, isolated stars. This error should be highly correlated between  $V$  and  $I$  measurements and thus not propagated through the reddening correction. However, to be conservative we instead adopt the entire ALLFRAME–DoPHOT distance modulus difference (0.10 mag) as an estimate of possible errors affecting only photometry for NGC 4258. Adding this in quadrature to the random error, the total uncertainty unique to our determination of a Cepheid distance to NGC 4258 is  $\pm 0.12$  mag.

This measurement is subject to a number of potential sources of systematic error that also affect Key Project distance determinations, as described in Table 1; their possible contributions have been

estimated to total  $\pm 0.18$  mag<sup>[19]</sup>. Further description of these sources of error may be found in Key Project papers<sup>[30]</sup>. Correcting for differences in heavy element content between the field we have studied and the LMC<sup>[20]</sup> using previously published studies of NGC 4258<sup>[21]</sup> would lead to an increase of  $0.08 \pm 0.06$  mag in the distance modulus we have derived. However, due to the lack of agreement on the magnitude and sign of this effect in recent studies, the Key Project has refrained from applying such corrections but considered the resulting uncertainty to be a possible systematic error. We thus do likewise, and obtain a Cepheid distance modulus to NGC 4258 of  $29.54 \pm 0.12$  mag (unique to this determination)  $\pm 0.18$  mag (systematic uncertainties in Key Project distances), corresponding to a metric distance of  $8.1 \pm 0.4$  Mpc  $\pm 0.7$  Mpc. When treated in the same way, the ALLFRAME results yield a distance modulus of  $29.64 \pm 0.09$  mag, corresponding to a metric distance of  $8.5 \pm 0.5$  Mpc. The distance to NGC 4258 derived from observations of Cepheids is thus appreciably greater than the maser distance of  $7.2 \pm 0.5$  Mpc<sup>[2]</sup>.

The Cepheid and maser distances differ by  $1.0\sigma$  if we add our measurement uncertainty of 0.4 Mpc, the Key Project systematic error estimate of 0.7 Mpc, and the maser distance error estimate of 0.5 Mpc in quadrature; potential systematic errors in either technique do not seem to have been grossly underestimated. If we assume that the maser distance is correct (up to its stated uncertainty) and wish to determine whether a revision of the Cepheid distance scale may be desirable, however, prior estimates of systematic errors in the Cepheid distance scale are irrelevant to calculations of significance. In that case, there is a  $1.3\sigma$  (80% significance) discrepancy ( $1.6\sigma$  if the masing disk is presumed to be circular). The largest potential source of such a difference in either error budget is the uncertainty in the distance modulus to the LMC; however, other identified potential sources of systematic error are great enough that a revision of the LMC distance is not required by our results.

A number of other tests of the extragalactic distance scale have been attempted in recent years using independent, physical or geometric methods; however, none of them currently have the same precision and direct applicability to recent Cepheid measurements that the maser distance

to NGC 4258 may provide in combination with our work. Observations of a “light echo” from Supernova 1987A have been used to place upper limits on the distance to the LMC; however, results differing by 10% in distance from each other have been obtained with this method<sup>[22, 23]</sup>, and it cannot place constraints on errors related to WFPC2 calibration or the effects of differences in chemical composition from the LMC. Interferometric radio observations of the expansion of SN1993J in M81 have been used to measure its distance with  $\sim 15\%$  uncertainty under modest assumptions<sup>[24]</sup>; the agreement with the HST Cepheid distance to its host galaxy is excellent<sup>[25]</sup>. However, the uncertainty in the distance to this supernova exceeds the estimated systematic uncertainties in the Cepheid distance scale, and the Cepheid distance to M81 was obtained with a different instrument (WF/PC) and photometric calibration techniques than were used for the majority of Key Project galaxies. Finally, distances to several Key Project galaxies have been obtained using the Expanding Photospheres Method on supernovae they hosted, again with good agreement. However, all of those supernovae were abnormal and considered *a priori* to be poor candidates for the method used; therefore, there may be substantial systematic errors in those EPM measurements, and drawing strong conclusions from this agreement may be questionable<sup>[26]</sup>.

Under the assumption that the maser distance and the estimates of its uncertainty are correct, we can derive the resulting absolute magnitudes of the Cepheids observed and obtain a potential recalibration of the Cepheid P–L relation; the details of such an analysis will be described in another paper (Newman *et al.* 2000, in preparation). Such a calibration could be significantly less subject to systematic effects than one based on ground-based observations of the LMC, as Cepheids in NGC 4258 should have a chemical composition similar to those in galaxies used by the Key Project to calibrate other distance indicators and have been observed with the same instruments, filters, and parameter measurement techniques used in other HST studies. To lowest order, extinction-corrected Key Project-like HST WFPC2 Cepheid results would be revised using the NGC 4258 maser distance simply by subtracting  $0.25 \pm 0.19$  mag from their distance moduli ( $0.33 \pm 0.20$  mag if a correction for differences in heavy element content from the LMC were made to the NGC 4258 Cepheid distance). Because the chemical composition of the field studied in NGC 4258 matches

the average for the Key Project galaxies used to calibrate most secondary indicators, if distances to both are corrected for differences from the LMC and then revised so that the Cepheid distance to NGC 4258 would match the maser distance, the net correction would remain 0.25 mag. The results for NGC 4258 thus would imply that typical HST WFPC2 Cepheid distances may be too high by  $12\% \pm 9\%$  ( $18\% \pm 9\%$  if the ALLFRAME results were adopted). It may be worthwhile to note that if applied to all WFPC2 Cepheid distances, such a correction would eliminate the discrepancies between the Tully-Fisher relation calibrated using ground-based distances and that obtained using Key Project results<sup>[27]</sup>, reducing its overall scatter accordingly. If such a comparison is fair, this suggests that the difference in the maser and Cepheid distances may be more likely to be due to the difficulty of WFPC2 calibration than to an error in the assumed LMC distance. However, selection effects or systematic errors in measuring the total galaxy magnitudes of the ground-based calibrators, which are relatively large in angular extent, could also explain the Tully-Fisher discrepancy, as those magnitudes are required for determining such distances. Revising Cepheid-calibrated distance indicators according to the maser distance would **increase** the measured Hubble constant by  $12\% \pm 9\%$ , and **decrease** the corresponding age of the Universe similarly. The resulting values would be increasingly difficult to reconcile with globular cluster ages unless the Universe has very low density or, particularly, if it has a nonnegligible cosmological constant or similar negative-pressure component<sup>[28]</sup>.

However, the statistical significance of such a revision remains limited. A more compelling test of the HST Cepheid distance scale based on the maser distance to NGC 4258 would require a substantially larger sample of Cepheids (reducing the uncertainties in determining the  $VI$  P–L relations and the reddening) and better determination of aperture corrections; these issues can be addressed simultaneously by searching for Cepheids with HST in a field that contains more stars and has undergone more recent star formation. It would be reasonable to expect that observations of a region richer in Cepheids might yield 3 times as many Cepheids (giving a distance modulus uncertainty of 0.04 magnitude) and aperture corrections accurate to  $\pm 0.04$  magnitude; better agreement between ALLFRAME and DoPHOT analyses might also occur with improved data.

Reductions of uncertainties in the maser distance, e.g. via improved constraints on the eccentricity of the circumnuclear disk, would also be greatly beneficial for its use to calibrate the extragalactic distance scale. Successful maser distances to other galaxies, establishing a Hubble relation, would more firmly establish this novel technique. With improvements in both Cepheid and maser analyses, NGC 4258 has great potential for establishing a new primary step in the distance ladder, reducing the potential systematic errors in measurements of the Hubble constant to perhaps as little as 5%.

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### Figure and Table Captions

**Figure 1** – Light curves for three representative examples of the Cepheids we have discovered in NGC 4258. Open symbols depict the measured magnitudes of a given star, and the error bars the uncertainty therein; the solid lines show template Cepheid light curves derived from observations of stars in the LMC<sup>[29]</sup> that have been used to fit the data. The left panel for each star shows the variation of the  $V$  magnitude of each star versus the the phase of the variation, which makes the Cepheid pulsation pattern clear. The right panel plots the  $I$  variation of the Cepheids in similar fashion.

**Figure 2** – NGC 4258 Period–Luminosity relations. **a**, The  $V$  P–L relation for the Cepheids we have found in NGC 4258, based upon DoPHOT photometry. The Cepheid P–L relation has previously been found to be well fit by a linear relationship between mean magnitude and the logarithm of the period in the range 10–60 days. To minimize the effects of incompleteness and

to optimize results given the limited number of Cepheids observed, we adopt LMC P–L relation slopes<sup>[3]</sup> and only fit for differences in the zero point. Open symbols depict the measured parameters of NGC 4258 Cepheids; the solid line indicates the fit P–L relation, and the dashed lines the  $2\sigma$  observed scatter of fiducial LMC Cepheids about its P–L relation. From the difference between the absolute magnitudes of LMC Cepheids (for an assumed LMC distance of 50 kpc) and the observed magnitudes of NGC 4258 Cepheids we derive a  $V$  distance modulus, defined by  $\mu = 5\log_{10}d/10\text{pc}$ , of  $\mu_V=29.82 \pm 0.07$  (ALLFRAME results yield  $29.88 \pm 0.08$ ). This value must be corrected for the effects of dust extinction to yield a reliable measurement of the distance of NGC 4258. **b**, The  $I$  P–L relation for NGC 4258 Cepheids. Applying procedures similar to those for  $V$ , we derive an  $I$  distance modulus  $\mu_I=29.71 \pm 0.05$  (ALLFRAME photometry yields  $29.78 \pm 0.05$ ). Correcting for the effects of dust on the apparent magnitude of each star using its observed colour, we obtain an extinction-corrected distance modulus of  $29.54 \pm 0.07$  mag from DoPHOT photometry for all Cepheids; those on WFPC2 chip 2 alone yield  $29.58 \pm 0.12$ , while those on chip 3 yield  $29.51 \pm 0.09$  (for ALLFRAME photometry, the corresponding numbers are  $29.64 \pm 0.08$ ,  $29.50 \pm 0.12$ , and  $29.74 \pm 0.10$  mag).

**Table 1** – A summary of the major identified errors which may affect our extinction-corrected distance modulus measurement. All numbers listed are in magnitudes; for small differences, the corresponding fractional error in distance may be obtained by multiplying by 0.46. For those potential systematic errors which affect all Cepheid distances obtained in the same manner as ours uniformly, we have adopted the uncertainty estimates of the Key Project<sup>[30]</sup>; more detailed descriptions may be found therein. The estimated systematic errors in WFPC2 photometry ( $S_2$ ) include uncertainties in zero points and the ‘long versus short’ uncertainty, added in quadrature. Because the metallicity of the field we have studied in NGC 4258 matches the average metallicity of Key Project galaxies used to calibrate the Tully-Fisher relation, surface brightness fluctuation distances, and the peak luminosities of Type Ia supernovae, we treat the uncertainties in metallicity

correction as a systematic error common to this distance measurement and those of the Key Project ( $S_3$ ). The random uncertainty in the Cepheid distance modulus ( $R_1$ ) has been estimated from the standard error of the extinction-corrected moduli for individual stars. We have adopted a conservative estimate of the total photometric uncertainties unique to NGC 4258 ( $S_4$ ) of 0.10 mag based on the difference between the overall distance moduli they yield. For chip 2, the mean difference between ALLFRAME and DoPHOT magnitudes for 24 bright, isolated stars was  $0.026 \pm 0.049$  (standard deviation) mag for  $V$ , and  $0.015 \pm 0.049$  mag for  $I$ . For chip 3, the mean difference for 30 stars was  $0.025 \pm 0.027$  mag for  $V$ , and  $0.088 \pm 0.046$  mag for  $I$ . Mean magnitudes for Cepheids yielded results consistent with these to within  $1\sigma$ , albeit with much larger standard errors. We consider the chip 3/ $I$  results to be an aberration closely related to the discrepant distance moduli obtained with ALLFRAME on the two chips; even including it, the mean ALLFRAME-DoPHOT magnitude difference among the 4 cases would be 0.04 mag.

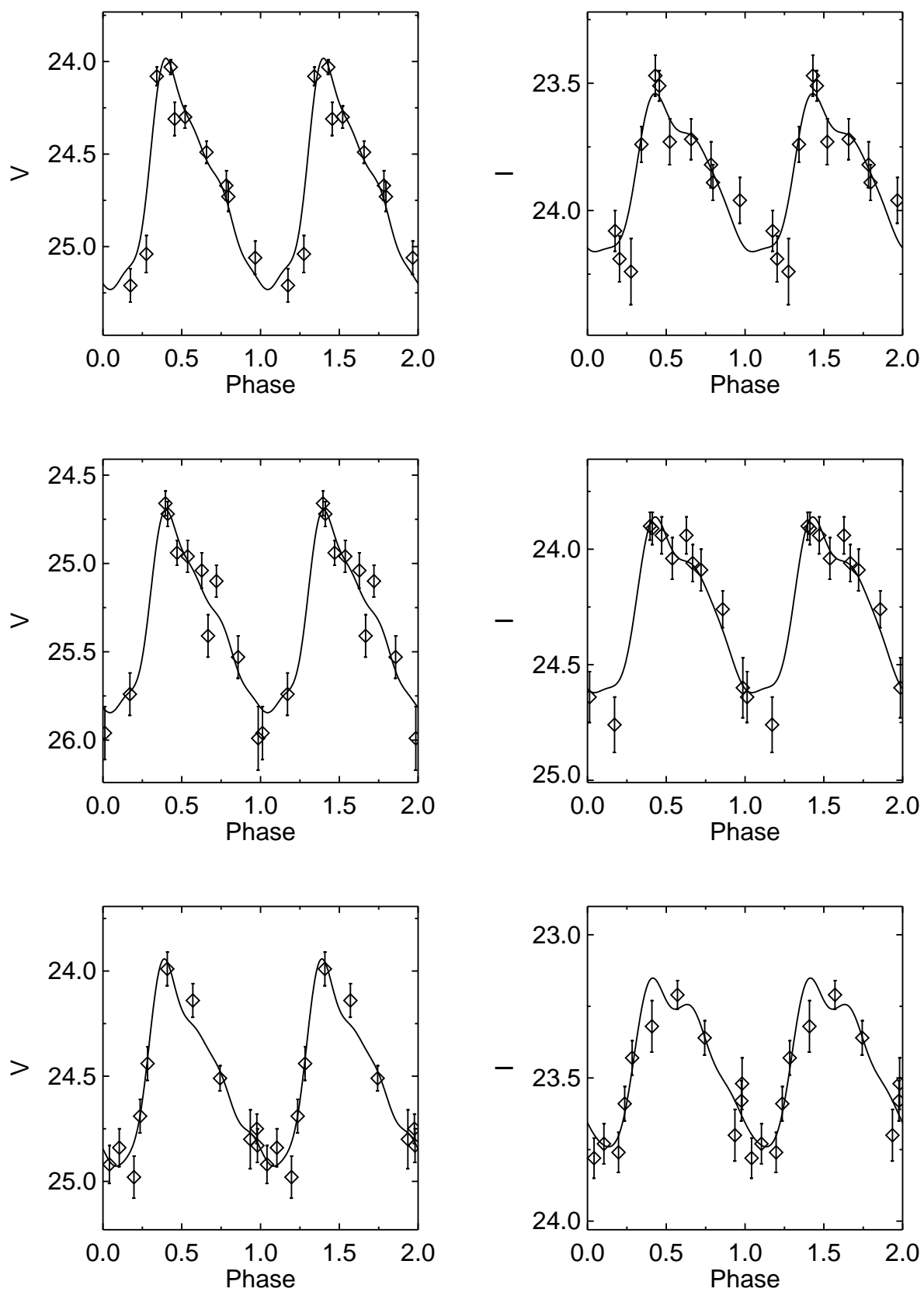


Figure 1

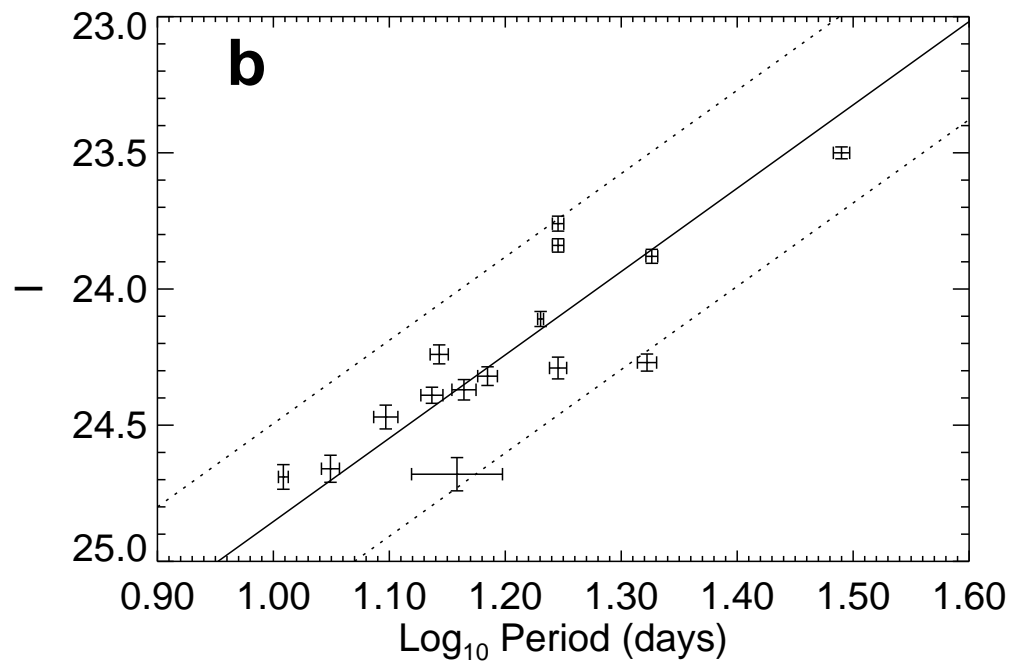
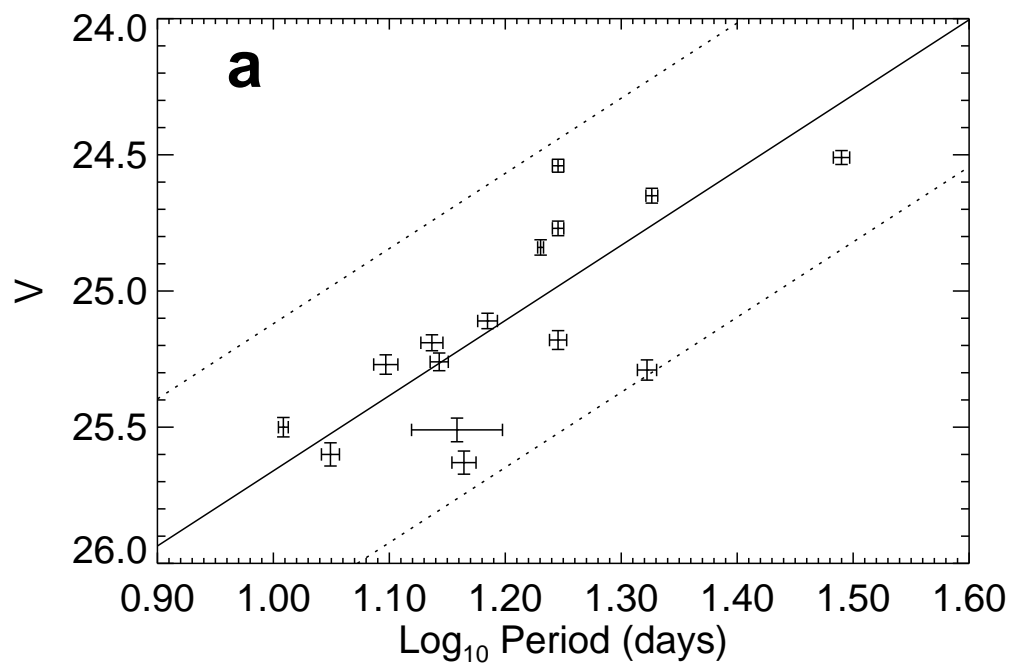


Figure 2

Table 1. UNCERTAINTIES IN THIS DISTANCE MEASUREMENT

	Source	Error
S <sub>1</sub>	Systematic Errors in LMC P-L Calibration	
	<i>A. LMC True Modulus</i>	±0.13
	<i>B. LMC P-L Zero Point</i>	±0.02
	A and B added in quadrature	±0.13
S <sub>2</sub>	Systematic Errors in WFPC2 Photometry	
	<i>C. HST WFPC2 V-Band Zero Point</i>	±0.03
	<i>D. HST WFPC2 I-Band Zero Point</i>	±0.03
	$\sqrt{C^2(1 - R)^2 + D^2R^2}$ , $R = A(V)/E(V - I)$	±0.09
S <sub>3</sub>	Average Metallicity Correction	+0.08±0.06
S <sub>4</sub>	Systematic Errors Unique to NGC 4258 Photometry (from DoPHOT-ALLFRAME comparison)	±0.10
R <sub>1</sub>	Random Error in the NGC 4258 Extinction-Corrected Distance Modulus	
	<i>G. NGC 4258 P-L Fit (V)</i>	±0.07
	<i>H. NGC 4258 P-L Fit (I)</i>	±0.05
	G and H partially correlated	±0.07
R <sub>tot</sub>	Errors Only Affecting This Determination (S <sub>4</sub> and R <sub>1</sub> added in quadrature)	± <b>0.12</b>
S <sub>tot</sub>	Systematic Errors in Techniques Used (S <sub>1</sub> , S <sub>2</sub> , and S <sub>3</sub> added in quadrature)	± <b>0.18</b>